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iSEDE DEMONSTRATOR ON HIGH ALTITUDE BALLOON BEXUS: INFLATABLE SATELLITE ENCOMPASSING DISAGGREGATED ELECTRONICS

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Traditional satellites have a rigid structure defining the basic configuration of the satellite and holding in place all subsystems. A variation of the shape or configuration of the satellite is normally achieved through the use of deployable structures or appendices (antennas, solar arrays, booms, etc.). Although modern structural solutions are modular and multifunctional, the structure of a satellite still represents a significant portion of its mass and a limitation on the achievable configuration, extension of deployable components and packing efficiency during launch. The goal of this project is to design and build an initial prototype of an all-inflatable satellite with disaggregated electronics for deployment on-board a BEXUS balloon as proof of concept. The idea is to use inflatable cell structures as support for all the subsystems composing a typical nano-satellite. Each subsystem and component is mounted on a different cell. Cells are both individually inflated and individually controlled. The aim is to design and build an inflatable satellite, demonstrating the deployment, communication among components and local control enabling structure shape adaption via soft robotic actuators and micro pumps. The experiment will deploy two inflatable structures made of 5x2 cells which are packed in a $10x10x10cm^3$ cubesat reaching a size of $70x18x14cm^3$ once deployed. Flexible circuitry was used to mount all the electronic subsystems on the surface of the folded inflatable. The experiment will be flown onboard the BEXUS16 stratospheric balloon to an altitude of 29km for 2-5 hours from the Swedish space port ESRANGE in October 2013.

I. ACRONYMS

BEXUS	Balloon-borne Experiments for University Students
CDR	Critical Design Review
COTS	Commercially Of The Shelf
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EAR	Experiment Acceptance Review
ESA	European Space Agency
GUI	Graphical User Interface
IPR	Interim Progress Review
iSEDE	Inflatable Satellite Encompassing Disaggregated Electronics
ISS	International Space Station
MORABA	Mobile Rocket Base (DLR)
REXUS	Rocket-borne Experiments for University Students
PCB	Printed Circuit Board
PDR	Preliminary Design Review
SSC	Swedish Space Corporation
SNSB	Swedish National Space Board
TC	Telecommand
TM	Telemetry
1U	One Unit (cube satellite) $10x10x10cm^3$
UART	Universal Asynchronous Receiver/Transmitter

II. INTRODUCTION

Space vehicle size is nowadays mainly governed by launch vehicle dimensions. The use of deployable structures became necessary due to their low stowage and high in-orbit volume. For the success of future

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space missions involving large space structure, the development of new deployable structures and the improvement of current designs are of great importance. Applications can be easily envisioned through truss structures, masts, crew quarters, transport tunnels, large solar arrays, solar concentrators, solar sails or antennas. A valuable option for these large ultra light structures is the exploitation of inflatables. Reasons for the use of inflatable structures range from their low cost over exceptional packaging efficiency, deployment reliability and low stowage volume to low weight. Over the last decades, inflatable structures became an emerging field to overcome launch vehicle payload size restrictions [1]. Research in inflatable structures can be dated back to the 1950s. The first major developments during this time showing the potential of these novel structural concepts were the Goodyear antennas in the early 1960s and the Echo Balloon series from the late 1950s to the early 1960s. The Contraves antennas/sunshades and the L'Garde, Inc., inflatable decoys followed in the 1970s and mid-1980s [2]. The biggest achievement up to date is the Inflatable Antenna Experiment (IAE) of L'Garde which was launched from a Space Shuttle- in May 1996[3] .

Research has been undertaken in various institutions all over the world in the field of inflatable structures [4-6]; new membrane materials have been discovered that can withstand the space environment, advanced simulation tools were developed that capture the highly non-linear behaviour of the inflation process and rigidization techniques have been investigated making the structure non-reliant on the inflation gas after deployment [7-9]. The industry is focusing on a variety of applications of inflatable structures to enable future space flight at present. After 1996, inflatables were used as protection devices for planetary rovers, for example the inflatable balloons to soften the landings of the Mars rovers Pathfinder in 1996 and Spirit and Opportunity in 2003.

Various companies are working on the use of inflatable antennas, reflectors, booms and solar arrays as satellite components. Just recently the company Space Ground Amalgam working on these inflatable satellite structures won a 100k prize in the Space Frontier Foundation's NewSpace business plan competition [10]. Other research is carried out in inflatable boom experiments like the CFRP Booms from the German Aerospace Center (DLR) [11]. Also NASA is working on inflation based structures which lead to a successful test of the Inflatable Reentry Vehicle Experiment (IRVE-3) in July 2012. The most ambitious plan comes from Bigelow Aerospace which has the target of building a Commercial Space Station consisting of inflatable modules. In January 2013, Bigelow Aerospace was contracted by NASA to build an inflatable module called BEAM to be tested on the International Space Station (ISS) during 2015 to 2017 [12].

Various space structures are serving just one specific purpose in space systems nowadays. By developing a structure that can adapt itself to various mission stages, the flexibility of the entire mission can be enhanced. With applying smart structures, the spacecraft can easily adjust itself to the space environment and expensive on-ground simulation to verify the accuracy of the structure when subjected to the harsh space environment become no longer necessary. These kind of smart structures have various applications in space systems. Examples of these structures range from telecommunication over earth observation to human space missions. For example, these structures can form antennas or concentrators which are able to adjust their focal point autonomously depending on their orientation towards the sun or their position in orbit. By using a smart membrane as a substructure for a solar sail, attitude control of the solar sail can be achieved by changing the shape of the structure and therefore varying the area subjected to the solar wind. This area change will result in an attitude change of the space craft.

By distributing the electronics over the surface of the inflatable smart structure, a very lightweight giant structure in space can be created without having the need for any rigid heavy substructures which would be dead weight. These satellites with a high area to mass ratio would be a great way to ensure that the satellite will re-enter the Earth's atmosphere in the recommended 25 years to mitigate space debris.

II. DESIGN AND OBJECTIVES

As part of the research that is going on at the University of Strathclyde on smart deployable structures [13,14], the iSEDE project has the purpose to demonstrate the disaggregated electronics and autonomous behaviour required to successfully develop an adaptable, lightweight, inflatable space structure. The basic idea of such a system is an all inflatable satellite which consists of multiple inflated cells. These cells have the capability to change their volume in-between each other and therefore change the shape of the entire satellite. A few cells form own standing colonies with their own power system (solar + storage), micro controller, housekeeping system and wireless communication to other cell colonies. [15] The wireless link between the colonies enables fast re-configuration of the colonies and safes cabling mass. The iSEDE experiment in specific is focused on disaggregating the electronics, removing the need for a rigid structure containing the basic satellite subsystems. The design will demonstrate feasibility for space applications, and be deployed in a high-altitude environment to prove this.

The first objective of the iSEDE experiment is therefore to deploy the satellites made up of multiple cells via inflation and observe the deployment behaviour and to verify existing LS-DYNA simulations. To demonstrate disaggregated electronics with wireless communication between satellites is the second objective. The third objective is to demonstrate autonomous behaviour of the whole system. The fourth and last objective it to alternate the shape of the satellite via integrated soft robotic actuators and micro pumps.

III. EXPERIMENT DESIGN

The concept of the iSEDE experiment is to have two inflatable satellites on board the BEXUS gondola and a central controller, the hub. One satellite is deployed before launch and the other is deployed when the balloon reaches float altitude. When all satellites are deployed, communication between the satellites and the hub commences. The hub communicates with the ground station through the BEXUS E-Link. The ground station will be able to receive reports and give commands. For example, a command can be given to cause the satellites to change their shape through pumping air between cells on the satellites

III.I Mechanical Design

The main concern of the mechanical design is the size, shape, strength and mass of the experiment in order to fit inside the given volume of the BEXUS gondola. The iSEDE experiment consists of the inflatable satellites, the deployment modules, the hub, the camera housing and associated interfaces. Different constraints apply to each subsystem.

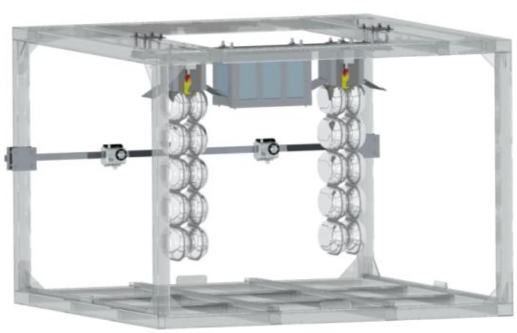

Figure 1: iSEDE experiment in BEXUS gondola

Inflatable Satellite

The deployed structure is entirely made of inflatable cells. It consists of two rows of 5 elongated ellipsoid cells deployed using the expansion of trapped air inside the ellipsoids when subjected to vacuum conditions. These cells are manufactured from an outer layer of adhesive Kapton and an inner layer of Mylar. These films are lightweight, strong and can withstand the temperatures that the experiment will be subjected to. The three middle cells (2, 3 & 4) are including a soft robotic actuator element which functionality is described later in the paper. This actuation element will not be affected by the harsh temperature but may degrade when subject to UV radiation.

Each cell has an un-inflated length of 18cm and height of 13cm with a 1cm seam. The deployable structure uses residual air inflation as a deployment mechanism. The inflation deformation of the cell is modelled using the equations established for the inflation of a flat circular shape presented in [14]. This predicts inflated dimensions of length 14.9cm, depth 5.9cm and height 9.9cm.

Figure 2: Inflated cell in vacuum chamber

A fully inflated, deployed structure with two columns of cells and no added mass would therefore have a size of 14.9x11.8x49.5cm^3. With added mass, around a 10% elongation is expected giving an inflated height of around 55cm.

Actuation

The actuation of the iSEDE inflatable is inspired by nature's heliotropism where motor cells in the plants stem change the pressure in-between neighbouring cells and therefore make the stem of the plant flex in order for the flower head to follow the sun over the course of a day [16]. This nature inspired principle is used for the shape alteration of the inflatable iSEDE satellite. Initially the concept was based around micro pumps being attached between two adjacent cells to change the cell's pressure and therefore their volume resulting in a deformation of the entire structure. But due to the inflexible nature of the used material Mylar, an other solution had to be created. A solution is the use of soft robotic elements which are made of highly flexible silicon rubber. Soft robotic elements usually have a cavity inside them which can be inflated causing a deformation of the element.

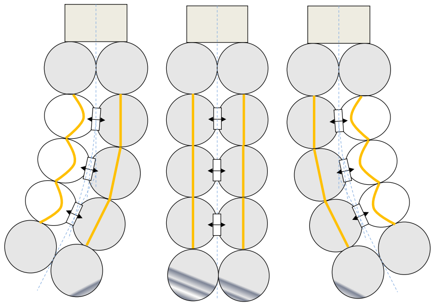

Figure 3: Actuation of satellites (soft robotic actuator = yellow lines)

The advantage of soft robotic elements is that they can be casted in every thinkable shape and their actuation performance can therefore be tailored. By mimicking this principle with micro pumps and soft robotic actuators, the iSEDE inflatable obtains the capability of changing its global shape (Figure 3). An actuator element consists of two soft robotic elements, one in each cell that is connected via a micro pump (Figure 4).

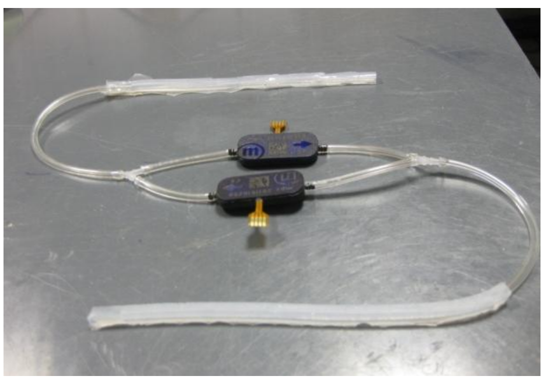

Figure 4: Actuator element consisting of two micro pumps for reversible flow and two soft robotic actuators.

During fabrication, a cavity inside the soft robotic actuator was created with a metal rod. In order to create the necessary higher stiffness on one side of the actuator to force the actuator to bend and therefore shorten, a thin nylon string is placed inside the actuator. If the soft robotic actuator gets inflated which would normally cause an elongation is now getting transformed in a bending of the actuator, which means an in plane shortening with a comparably high actuation force. During fabrication the actuator tool is placed inside a vacuum chamber to remove small air bubbles from the soft robotic actuators to improve the quality of the actuator.

<u>Deployment boxes</u>

The deployment modules are simple 1U (10x10x10cm) boxes made of lightweight but durable aluminium. The deployment method used contains a solenoid which is connected to a linkage arm which in turn is connected to a latch 9Figure 5). Once the solenoid is activated, the solenoid pin will retract; this will pull the linkage arm vertically upwards. This vertical movement will then cause the latch to pivot around the link between the linkage arm and the latch. This motion will then cause the hook of the latch to lose contact with the sprung hinged doors, hence, releasing the inflatable structure.

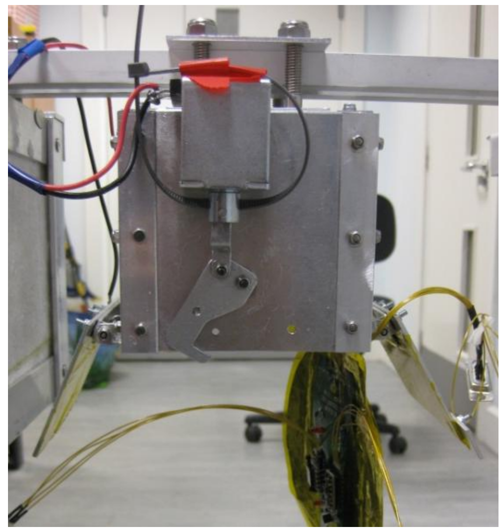

Figure 5: Deployment box with release mechanism

<u>Hub and experiment mounting</u>

The hub houses the central electronic intelligence and will act as the controller of whole experiment. The hub is manufactured from lightweight aluminium angles and polystyrene.

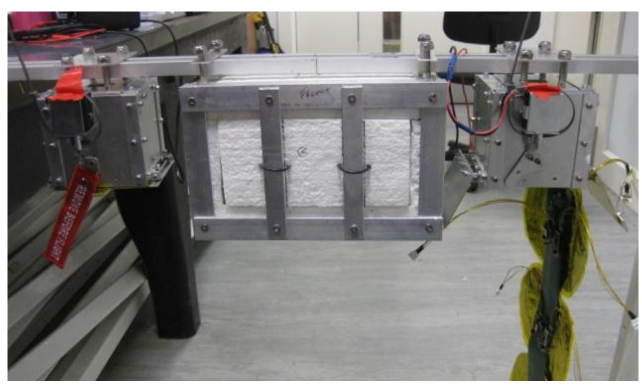

Figure 6: Hub mounted between the two cubesat boxes

The hub houses a Raspberry Pi controller, the power system and the data handing board. The hub also facilitates the physical electrical interfaces to the BEXUS service module, to both satellites and cameras.

To record the behaviour of the satellites, two HackHD cameras are mounted on the opposite wall of the hub. The GoPro housing of the HackHD cameras are mounted to an aluminium tube and can be easily adjusted to align with the inflatable satellites by of sliding the camera bracket along the aluminium tube.

The hub and both deployment boxes are mounted to two smaller aluminium tubes. These aluminium tubes will then be clamped to the roof of the BEXUS gondola by way of aluminium plates and M8 bolts.

III.II Electronic Design

All components in this experiment are COTS and have been selected as they have low mass, volume and footprint. Regarding to their datasheets, they should also work within the harsh environmental operating conditions. The system architecture is designed to be robust and fulfill its purpose with the minimum components and simplest implementation.

The electrical system can be divided into two subsystems, the Hub and the satellites. Although the experiment will launch two satellite units, the electrical systems on each are identical.

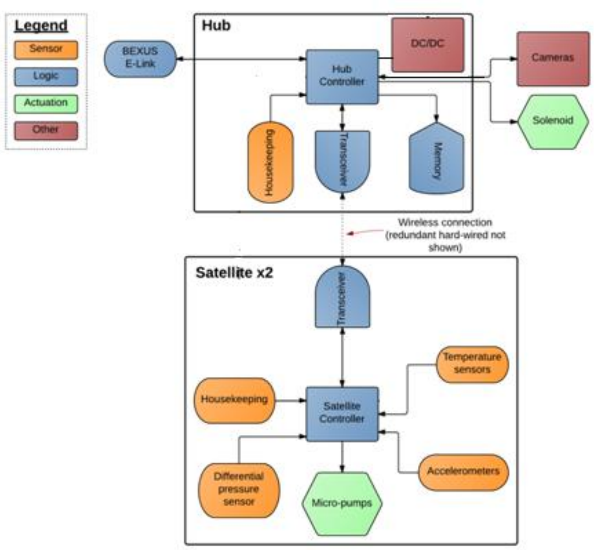

Figure 7: Block diagram of the full electrical system, excluding power distribution

The primary purpose of the electronics on board the Hub is to process collected data, save it to the SD card and transmit it through the BEXUS downlink to the ground support software. Additionally, it shall dictate the operation of the satellites throughout flight and relay commands sent from the ground support software to the respective satellite.

The Hub electronics consist of a data acquisition system, a microcontroller, a power distribution system and wireless transmission system. The Raspberry Pi processing unit controls the data acquisition system, communication with the satellites and ground station, experiment timeline, solenoid and operates the cameras.

All data received by the Hub over the wireless network is processed by the Hub for storage on the SD card and transmission through the BEXUS downlink to the ground support station.

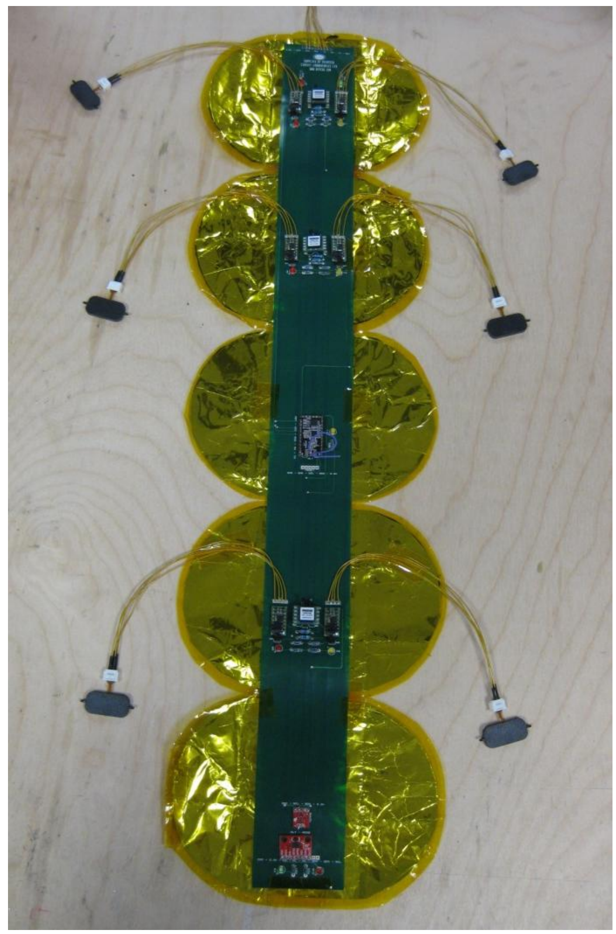

Figure 8: Full satellite with attached flexible circuit

Each satellite (Figure 10) contains a microcontroller, micro-pump actuators with control system, and a number of sensors for environmental readings and housekeeping. The satellite microcontroller's task is to receive commands from the transceiver; carry out actions accordingly; read sensor data and transmit it to the Hub; actuate the micropumps for shape alteration and implement closed loop control on the actuation process.

The control system on each satellite operates using readings from two accelerometers; one static accelerometer situated at the top of the satellite and another moving accelerometer located at the bottom cell of the satellite. It will ensure that the deformation of the structure due to actuation shall remain within pre-defined limits.

It is also worth noting that although a wireless link between Hub and both satellites exists, there will also be a hard-wired connection in case of an issue with establishing wireless communication.

Hub

The satellites must be monitored and deployed by the ground station. Ideally the communication would be directly from the ground to the satellite, but in order to simplify the experiment it was decided to use the BEXUS E-Link for communication between the ground and the balloon. A controller is needed to act as the interface between the E-Link and the satellites. As the E-Link uses Ethernet, the controller should be able to interface with Ethernet, and wirelessly to the satellites.

The Hub is based around Raspberry Pi model B running Raspbian “wheezy” which allows for seamless interfacing with the BEXUS E-Link and ease of programming whilst still providing the required functionality. The Raspberry Pi is linked directly to the panStamp wireless module via UART pins. This data is collected for processing and storage, as described. The temperature sensor is set to monitor the ambient temperature within the Hub unit.

Video cameras are used to record the deployment and actuation of the satellites. This visual data is a significant part of the scientific return of the experiment. As capturing video footage of deployment and actuation is so significant, it is a requirement that the cameras must run as a standalone system. As a result, there is no video-processing requirement for the Hub, simplifying its hardware and software requirements. HackHD cameras are used as they fit these requirements.

Satellites

Each satellite forms the basis of what would be a concentrated control hub as part of a larger smart space structure. As such, its electronics are designed to facilitate an intelligence of performing various measurements to monitor and control the performance of the structure. Each satellite gathers ambient and component temperature readings along with important voltage sensing for housekeeping. Differential pressure measurements are also being taken to help characterise the inflation of the structure at deployment and throughout flight.

As described earlier, the actuation is driven by Bartels micro pumps which are connected electrically to the microcontroller through their own sub-controller (Figure 9). The control of the actuation is provided through two accelerometers positioned on the structure.

Data is not stored on each satellite; it is instead only acquired and transmitted to the Hub via the wireless link. The data is then processed, stored and sent to the ground support station.

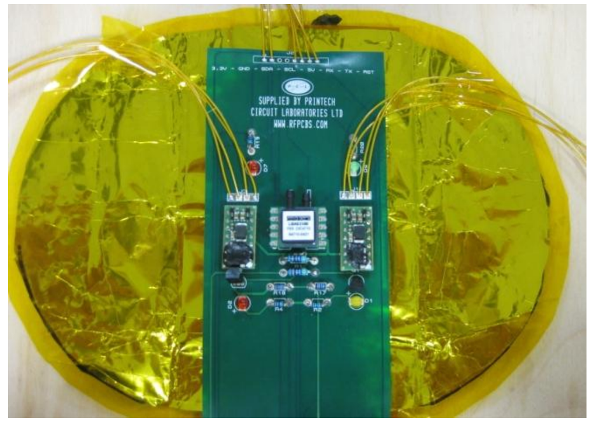

Figure 9: Top cell of satellite with pump/pressure sensor unit (cables towards micro pumps)

The satellite controller circuit is a panStamp based upon the Arduino Pro Mini. It uses an Atmega328 chip and the open source schematics & firmware made available by panStamp.

III.III Software Design

As described, only one satellite shall be deployed at float altitude, with the other being pre-deployed before launch. The deployable satellite shall be actuated following a command given manually from the ground support software. Both satellite systems shall be on standby from launch and fully activated upon receipt of the deployment command.

Throughout the experiment, the Hub acts as the primary experiment controller; dictating the operation of the experiment depending on the experiment timeline and user commands from the ground support station.

The software implemented across the experiment shall act to serve two main purposes:

1) On board data handling
2) Experiment control and operational timeline

For the on-board data handling, each satellite shall monitor its own deployable structure during adaptive phases, carry out various measurements to be stored and sent to the hub, and perform standard housekeeping. Temperature readings are taken from critical component during the flight to recognize occurring problems early. Cameras will capture the deployment and shape alteration throughout the flight; however, the cameras selected are COTS products capable of carrying out their own data processing and storage. Data collected by each satellite is sent to the Hub and stored on SD card there.

The software operates in one primary mode once the satellite is fully deployed and systems are online which is called the operational phase. The operational phase runs for 60 minutes and will be repeated until the BEXUS balloon will be cut to initiate re-entry.

Table 1: Operational Phase: Pump Actuation

OP	Satellite 1	Satellite 2
+0	Pump 1 (+)	Pump 1 (-)
+10	Pump 1 (+) & 2 (+)	Pump 1 (-) & 2 (-)
+20	Pump 1 (+), 2 (+), 3 (+)	Pump 1 (-), 2 (-), 3 (-)
+30	All pumps off	All pumps off
+40	Pump 1 (-)	Pump 2 (+)
+50	Pump 1 (-) & 2 (-)	Pump 2 (+) & 3 (+)
+60	**Full Cycle Complete. Repeat until descent when systems go on standby.**	

Table 1 shows which pumps are activated during the operational phase. During this phase both satellites keep on recording data from the accelerometers, temperature sensors and pressure sensors and communicate them via wireless to the hub.

Hub

The hub acts as the main experimental controller for the iSEDE experiment. Its tasks primarily include controlling the experiment timeline, storing data and allowing communication between the satellites and ground station through the BEXUS E-Link.

The Hub co-ordinates each satellite according to the experimental timeline and commands received from the ground station. The Hub will also ensure that the experiment shall not deploy until deemed safe by the ground-crew; a 'go' command will be sent once the balloon has reached the float altitude of its flight. Upon receiving this command, the first cycle of the experimental timeline will initiate. The cameras used automatically begin recording and storing data upon receiving command from the hub; they are set to record through all operational phases carried out during the flight. Across the full flight, the Hub will generate reports based upon critical data received from each satellite and transmit these through the BEXUS E-Link to the ground station. Additionally, the Hub may have the capability of receiving requests to generate bespoke reports at any time during the flight, from the ground station.

Satellites

Each satellite deployed shall implement the same control and data handling techniques. The main focus of each system is control of the inflatable structure; however, many other functions are present. Each satellite shall perform its own housekeeping; measuring ambient & component temperature.

Ideally, control of the inflatable structure during its adaptive phase shall be implemented by use of a closed loop feedback system. Development of a control loop has been of particular focus since Preliminary Design Review and has resulted in the decision to use the two ADXL345 accelerometers as input parameters (Figure 10). The output from both accelerometers allows the orientation of the tip of the satellite to be determined. This orientation is indicative of the level of actuation achieved and is fed into the control loop. These values can then be used as a reference for the control loop to ensure the structure reaches its defined shape alteration during each activation cycle.

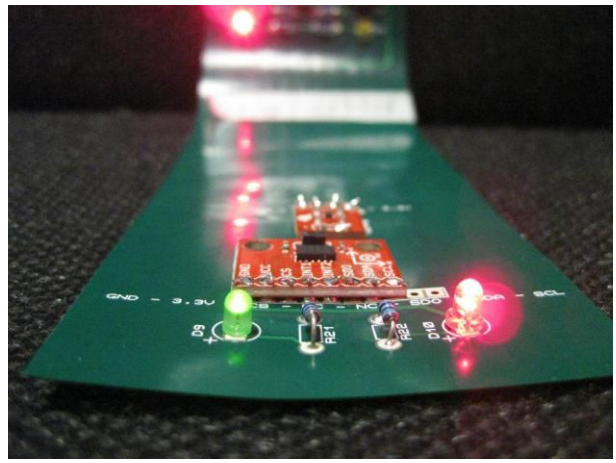

Figure 10: Accelerometer and temperature sensor placed on bottom cell of satellite

Ground Support

The ground support software (Figure 11) consists of a graphical interface to enable the controller to easily interact with the experiment.

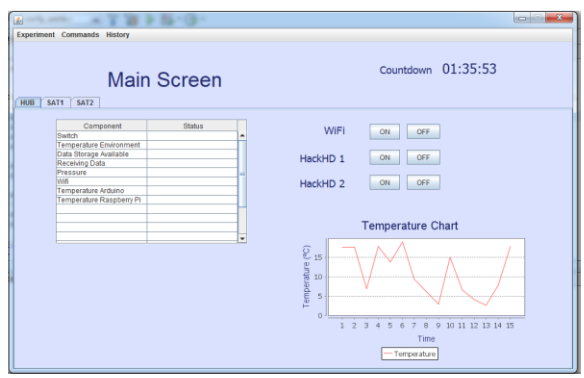

Figure 11: Main screen displayed during flight showing the most important data of the iSEDE hub

The software is able to receive telemetry (TM) from the experiment and send the telecomands (TC) to control the experiment. One of the most important TCs is the firing of the solenoid to release the undeployed satellite. Due to the fact that the firing of the solenoid can only be done once during the mission (satellite will deploy), a pop up asks the user for a second confirmation. An accidental triggering of the deployment will be prevented.

An additional webcam based camera is added opposite the hub giving the ground controller the possibility to see what is happening in the gondola in real time.

IV. LAUNCH CAMPAIGN AND MISSION

The BEXUS 16/17 launch campaign is from the 4th until 14th of October from ESRANGE space centre close to Kiruna in Northern Sweden. It is scheduled that the iSEDE experiment will fly onboard BEXUS16 to a float altitude of 29km which will last for 2-5 hours depending on wind.

At the launch of the BEXUS balloon, one of the deployable satellites will be already deployed to record the inflation of the cells by the decreasing environmental pressure. In this phase the accelerometers and cameras will record the behaviour of this satellite. In the meantime, the second satellite is folded and stored in the second deployment box. The BEXUS balloon should reach float altitude after 45 minutes. Once there is no more movement of the gondola, the second inflatable satellite is deployed via the solenoid triggered release. The deployment is monitored by the HackHd cameras, webcam and the accelerometers. In the following stages the micro pumps in both satellites get activated to pump the actuation fluid from one actuator to the other, this in turn deforms the whole structure. The actuation cycle lasts one hour and will be continued until the signal for balloon cut down is given. During the entire float phase, the wireless communication between the satellites and hub is validated. At the cut down of the balloon, the cameras and sensors will record the satellites structural behaviour during the fall. It is expected that micro gravity will exist for a fraction of a second of the free fall. During the entire mission, temperature and status readings are collected from critical components to observe the behaviour of the COTS components under these harsh environmental conditions.

V. ACKNOWLEDMENTS

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V. CONCLUSIONS

The iSEDE experiment will be launched at the BEXUS16/17 campaign on a stratospheric balloon flight to an altitude of around 29km for 2-5 hours. The experiment has the purpose to prove the concept of distributing the electronics of a conventional satellite on the surface of an inflatable satellite and therefore opening the possibility to decrease the weight of spacecrafts. Two inflatable satellites are each made up of a row of 5x2 self inflating cells which are capable of changing the shape of the structure with embedded soft robotic actuators controlled by micro pumps. All the electronics are disaggregate over the surface of the cells via flexible circuit boards. The two satellites are able to communicate with the Hub over wireless communication to prove the idea of assembling a larger structure made up of multiple self sustaining inflatable colonies with their own controller, power and shape changing capability.

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